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Mapping Surface Soil Moisture with L-Band Radiometric Measurements

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Radiometric measurements were made over two small watersheds with a four-beam pushbroom microwave radiometer aboard the NASA C-130 aircraft, during a dry-down period following a heavy rainfall in May and June 1987. The two watersheds were in the tall grass prairie region of Kansas. One of them was burned about 2 months prior to the measurements and the other was not burned for more than a year. Surface (0–5 cm) soil moisture data were collected close to the times of the aircraft measurements and correlated with the corresponding radiometric measurements. This established a relationship required for the mapping of surface soil moisture in these watersheds. It is shown that the radiometric sensitivity to soil moisture variation is higher in the burned watershed than in the unburned watershed. A comparison of the derived soil moisture contours also shows that the burned watershed loses surface soil moisture more rapidly than the unburned watershed.

INTRODUCTION

The experiments on passive microwave remote sensing of soil moisture have been conducted for nearly two decades (Schmugge et al., 1986, and references therein). These efforts were primarily studies of the dependence of the microwave emissivity on factors such as soil moisture and texture, surface roughness, and vegetation. It was generally agreed that the emissivity measurements at L-band (a wavelength of about 21 cm) could give reasonable estimates of surface (top 0–5 cm layer) soil moisture. With this capability, it was proposed to use an airborne radiometer operating at the 21-cm wavelength to map surface soil moisture patterns as part of the International Satellite Land Surface Climatology Project's (ISLSCP) first field experiment (FIFE). The proposed instrument is the recently developed four-beam L-band pushbroom microwave radiometer (PBMR) (Harrington and Lawrence, 1985), which has been flown over test sites in eastern Maryland (Jackson and O'Neill, 1987), the Texas panhandle (Jackson et al., 1987) and an agricultural area near Fresno, California (Wang et al., 1987). It was shown that the instrument is capable of producing two-dimensional brightness temperature maps which were used to infer spatial soil moisture patterns. A calibration of the radiometric response with appropriate ground truth data should enable one to obtain the soil moisture maps. The subject of this paper is the temporal mapping of spatial soil moisture patterns as the watersheds dry down from a saturated state.

Examples of soil moisture contours retrieved from the L-band radiometric measurements are

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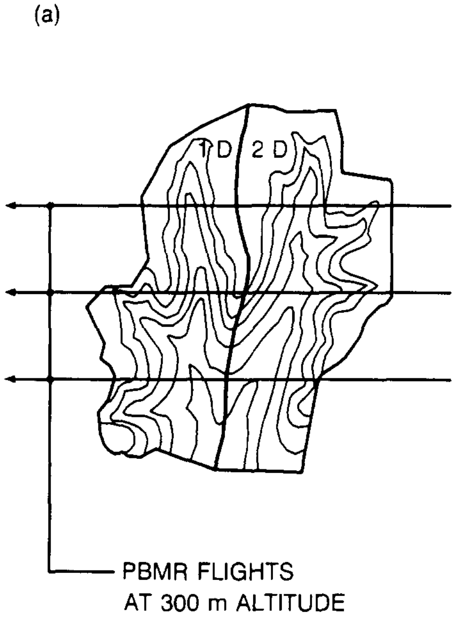
shown for two small watersheds in the Konza Prairie a few kilometers south of Manhattan, KS. The radiometric measurements were made as a part of the First ISLSCP Field Experiment (FIFE). Four intensive field campaigns (IFC) over a total of 56 days were conducted during 26 May–16 October 1987. The results reported below were derived mostly from the first IFC of 26 May–6 June when a nearly complete dry-down of soil moisture was observed. Four days of measurements on May 28, 29, and 30 and June 4 were made during this period.

THE MEASUREMENTS

The radiometric measurements over two small watersheds were made with an L-band pushbroom microwave radiometer (PBMR) aboard the NASA C-130 aircraft. The PBMR has four beams pointing at $\pm 8°$ and $\pm 24°$ from the nadir. Each of the beams has a full width at half-maximum power of about 16° so that the total swath is about 1.2 times the aircraft flight altitude. The interested readers are referred to the reports of Harrington and Lawrence (1985) and Schmugge et al. (1988) for a detailed description of the instrument. Additional instruments aboard the aircraft are the PRT-5 radiometer, the NS001 Thematic Mapper Simulator, and the Thermal Infrared Multispectral Scanner.

Figure 1a) shows the three flight lines along the east–west direction, which at an altitude of about 300 m give nearly complete coverage of the two watersheds. They are located at approximately 39°04′50″ N latitude and 96°33′34″ W longitude, which is about 15 km south of Manhattan, KS in the Konza Prairie Research Natural Area. The size of the two watersheds is approximately 1.2 km in the north–south direction and 0.8 km in the east–west direction. Ground soil moisture samples were obtained along three transects under the flight lines close to the times of the aircraft measurements. The soil moisture samples were taken in the top 5-cm layer at about 50-m intervals along each transect. Bulk density measurements were also made near these sampling locations in order to obtain volumetric soil moisture. The western watershed (1D) is burned every year, while the eastern one (2D) is burned every other year and was last burned in 1986. As a result of this burning sequence, 1D was covered only with lush green

Figure 1. a) The sketch showing the watersheds 1D and 2D, and the flight lines of the NASA C-130 aircraft at 300 m altitude. b) The variations of the average daily rainfall amount over Konza Prairie and the ground measured volumetric soil moisture (0–5 cm) in watershed 1D and 2D.



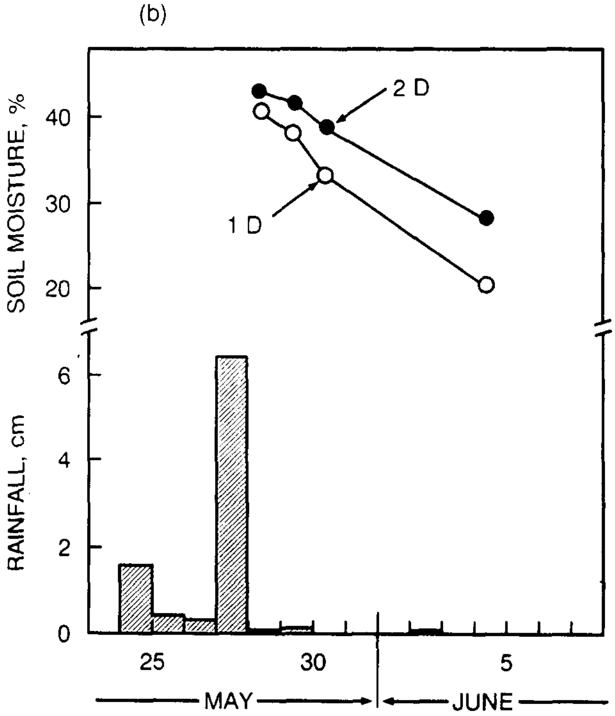


Table 1. The Average and the Range of Volumetric Soil Moisture Values Sampled for Watersheds 1D and 2D during the First IFC

	1D 21 samples			*2D 26 samples*		
Date	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*	*Minimum*
28 May 1987	40.5	51.1	32.3	43.1	53.7	32
29 May 1987	38.0	48.7	25.2	41.8	51.0	29
30 May 1987	33.3	44.8	21.0	38.6	48.8	26
4 June 1987	20.2	28.1	10.6	28.1	40.1	16

vegetation between 20 and 30 cm high. While 2D had about the same amount of green vegetation, it was mixed with senescent vegetation from the previous year and as a result had a greater amount of biomass above the soil. In 1D bare soil was generally visible through the green vegetation, which was not true in 2D.

Figure 1b) shows the total daily rainfalls over the Konza Prairie in the period during and immediately prior to the first IFC. It also gives the average volumetric soil moisture values from samples taken along the three transects in watersheds 1D (21 samples) and 2D (26 samples) on the days of the airborne radiometric measurements. The soils were moderately wet prior to May 27 when a heavy steady rainfall of more than 6 cm accumulation occurred. These soil moisture values and their ranges are also listed in Table 1. Thus, on the first day (28 May) of the radiometric measurements the soils in these watersheds were nearly saturated with a volumetric moisture content of about 42% No significant rainfall occurred throughout the rest of the IFC so that the four radiometric measurements covered the substantial portion of the dry-down in these watersheds. Notice from the figure that the rate of decrease in soil moisture is quite different for the two watersheds. Watershed 1D loses soil moisture much more rapidly than watershed 2D.

THE MEASUREMENT RESULTS

Figures 2a) and b) for watersheds 1D and 2D, respectively, show the normalized brightness temperature or effective emissivity (e) plotted as a function of volumetric soil moisture W in the top 0–5-cm layer, where e is defined as the ratio of the brightness temperature measured by the PBMR to the surface temperature measured by the PRT-5 radiometer aboard the C-130 aircraft. The open circles are the results of flights from FIFE in 1987, while the solid circles are derived from a few flights in 1985 (Schmugge et al., 1988). Each of the open circles represents the average e and W values derived for each watershed along a transect and the associated PBMR beam. All except the group of open circles at W values $< 15\%$ in each plot are derived from the first IFC. These data representing the driest soil condition in each watershed were obtained in the fourth IFC 5–16 October 1987 and is included here to give a better range in the variations of soil moisture and microwave emission. The difference in the amount of biomass cover between the first and fourth IFCs will not affect the analysis results because there is little distinction in the microwave emission from bare or vegetation-covered soils when dry. Also the water content of vegetation in October will be low due to grasses going into senescence.

A linear regression applied to the 1987 data results in the equations and correlation coefficients indicated in the plots for watersheds 1D and 2D. Excellent correlation between e and W is obtained for both 1D and 2D data sets. The data derived from the 1985 flights (Schmugge et al., 1988) are quite comparable to those from 1987 flights. It is emphasized that the same calibration algorithm has been applied in the reduction of microwave data since 1984. No adjustment has been made in any of the calibration coefficients. This suggests that the PBMR has been extremely stable over this period, and the regression equations shown in the figure can be used to estimate soil moisture from the radiometric measurements, provided that these watersheds undergo similar surface treatments.

The aircraft's position as a function of time was determined using a nadir viewing video camera and drawn on the watershed map. These flight lines were digitized and used with the PBMR

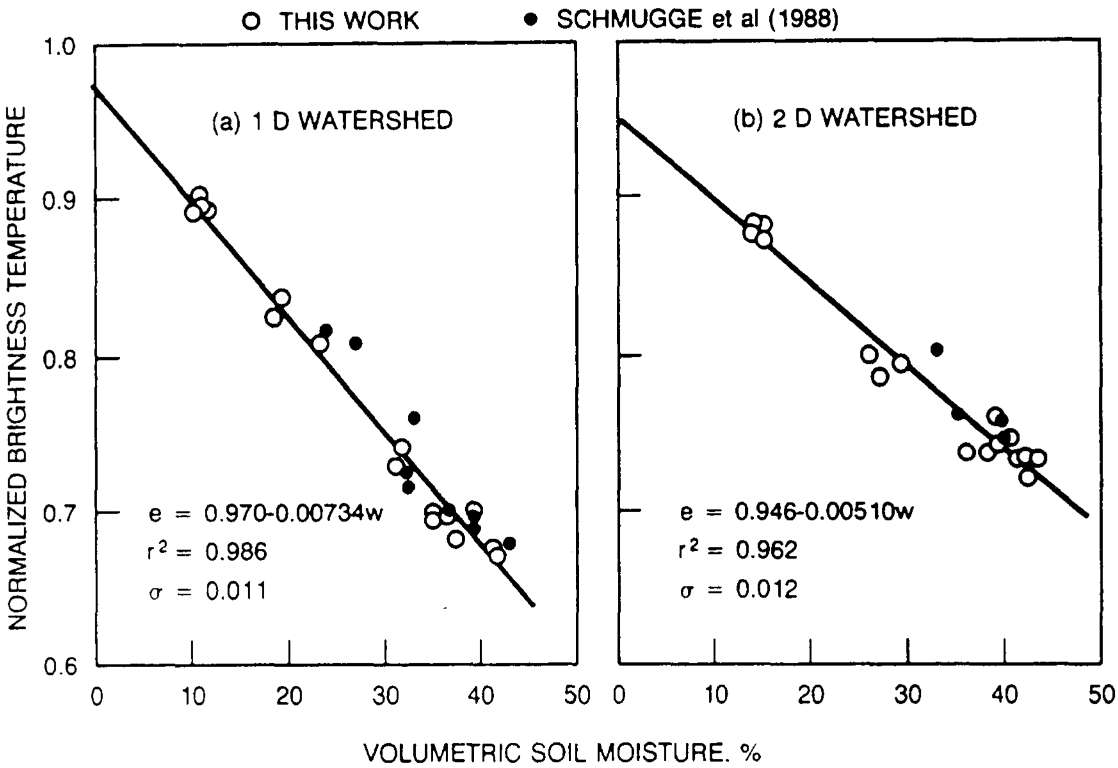


Figure 2. The correlation of normalized brightness temperature and volumetric soil moisture for a) watershed 1D and b) watershed 2D. The solid circles are the data obtained for the same regions in 1985 by Schmugge et al. (1988).

viewing geometry to produce brightness temperature maps of the watersheds. Although the regression given in Fig. 2 use radiometric data from only the beam associated with the transect of ground soil sampling, all four beams of PBMR have been calibrated with targets of known brightness temperatures (smooth water surface and 23 cm Eccosorb slabs at ambient temperature). Therefore, the regression equations can be applied to the data from all four beams to arrive at the two-dimensional mapping of soil moisture in the top 5-cm layer. This is done for the four days of measurements over these two watersheds during the first IFC. The results derived from the measurements on 28 May and 4 June are shown in Figs. 3 and 4, respectively. The numbers associated with the dashed contours indicate the volumetric soil moisture values in percent.

DISCUSSION

As noted earlier, the regressions of TBs versus soil moisture were in excellent agreement with those obtained in the 1985 flights over this area and also with results obtained over other pasture grass situations in Oklahoma (Jackson et al., 1984) and in South Dakota (Owe and Schmugge, 1983; Mo and Schmugge, 1983). The difference between 1D and 2D regressions was due to the dead vegetation from the previous year, which resulted in about a 20% decrease in sensitivity.

The soils for these watersheds were determined to be silt loams with a texture of 10% sand and 30% clay. If the Wang and Schmugge model (1980) for the dielectric constant of soil is used along with the Fresnel equation for the surface reflectivity/emissivity, a calculated curve of e vs W for a bare smooth soil with this texture can be determined. The result has a slope or sensitivity of 0.0094/unit soil moisture in the region between 10 and 40% moisture. Thus the slope of the regression for the data from 1D is about 73% that expected for the bare-smooth soil case and for 2D it is 51%. This reduction in sensitivity can be related to surface and vegetation factors by the equation (Schmugge et al., 1986)

$$e/SM = [e/SM]_{BS} * \exp(-h - 2\tau), \quad (1)$$

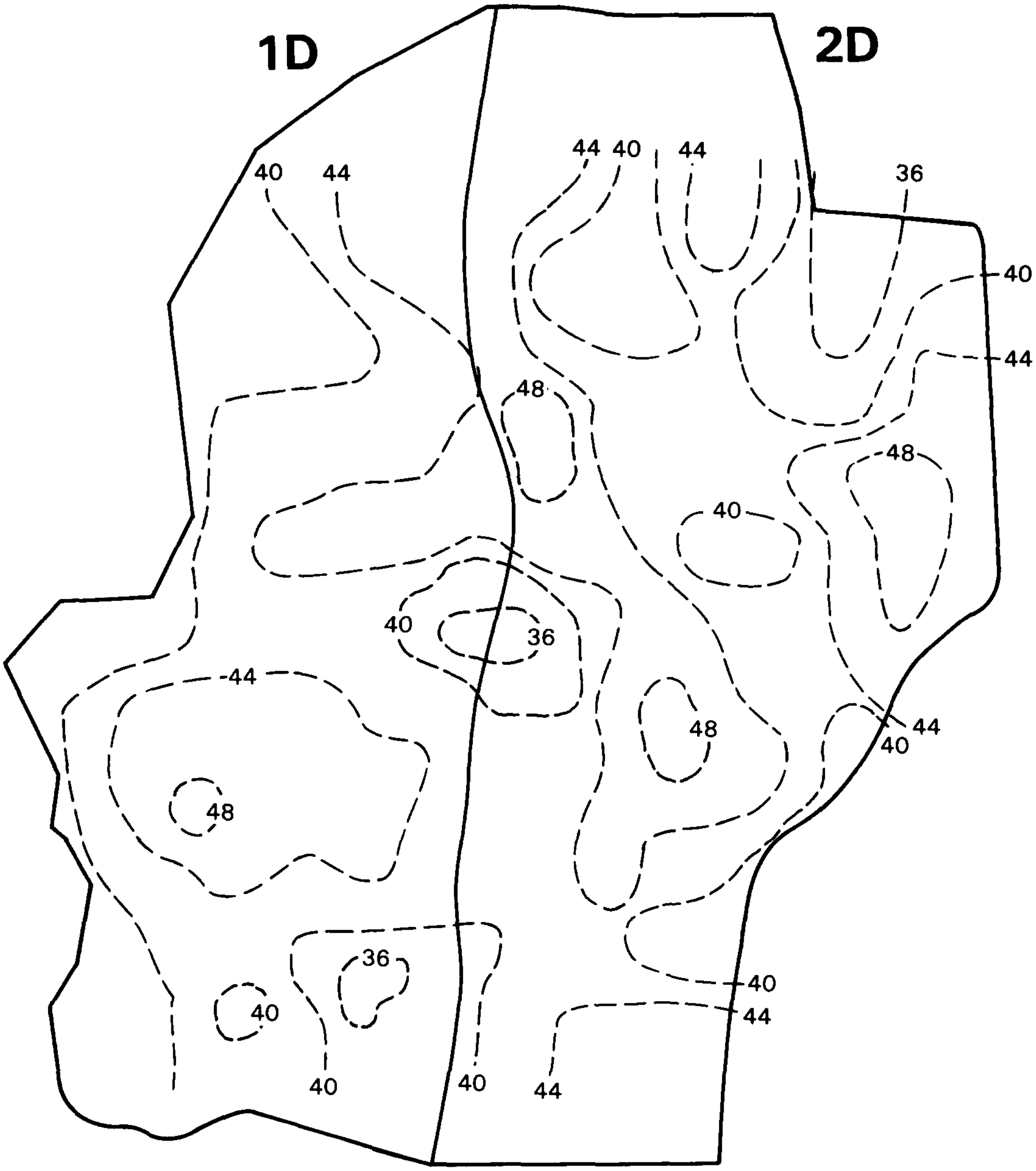


Figure 3. The soil moisture contours for the top 5-cm layer derived from the radiometric measurements on 28 May 1987.

where the subscript BS implies the slope for bare smooth soil case, h is the roughness factor (Choudhury et al., 1983) and τ is the vegetation absorption and is given by

$$\tau = 0.115 * W_{\text{veg}}, \tag{2}$$

where W_{veg} is the vegetation water content in kg/m^2. For our 1985 data W_{veg} was about 0.6 for the burned case and roughly double that for the unburned. This yields 2τ's of 0.14 and 0.28, respectively. The analysis of these values and eqs. (1) and (2) yields values of 0.1 and 0.33 for the two watersheds, which are within reason but we would have expected them to be closer together and around the value found for 1D. These results are summarized in Table 2.

A few features emerge from a comparison of Figures 3 and 4. First, when the soils are very wet after the heavy rainfall on 27 May, the moisture contours in Fig. 3 do not show a distinct boundary between the two watersheds. After a week of drying-down, the transition between these two watersheds becomes distinct. A steep gradient in soil moisture develops across the middle portion of the

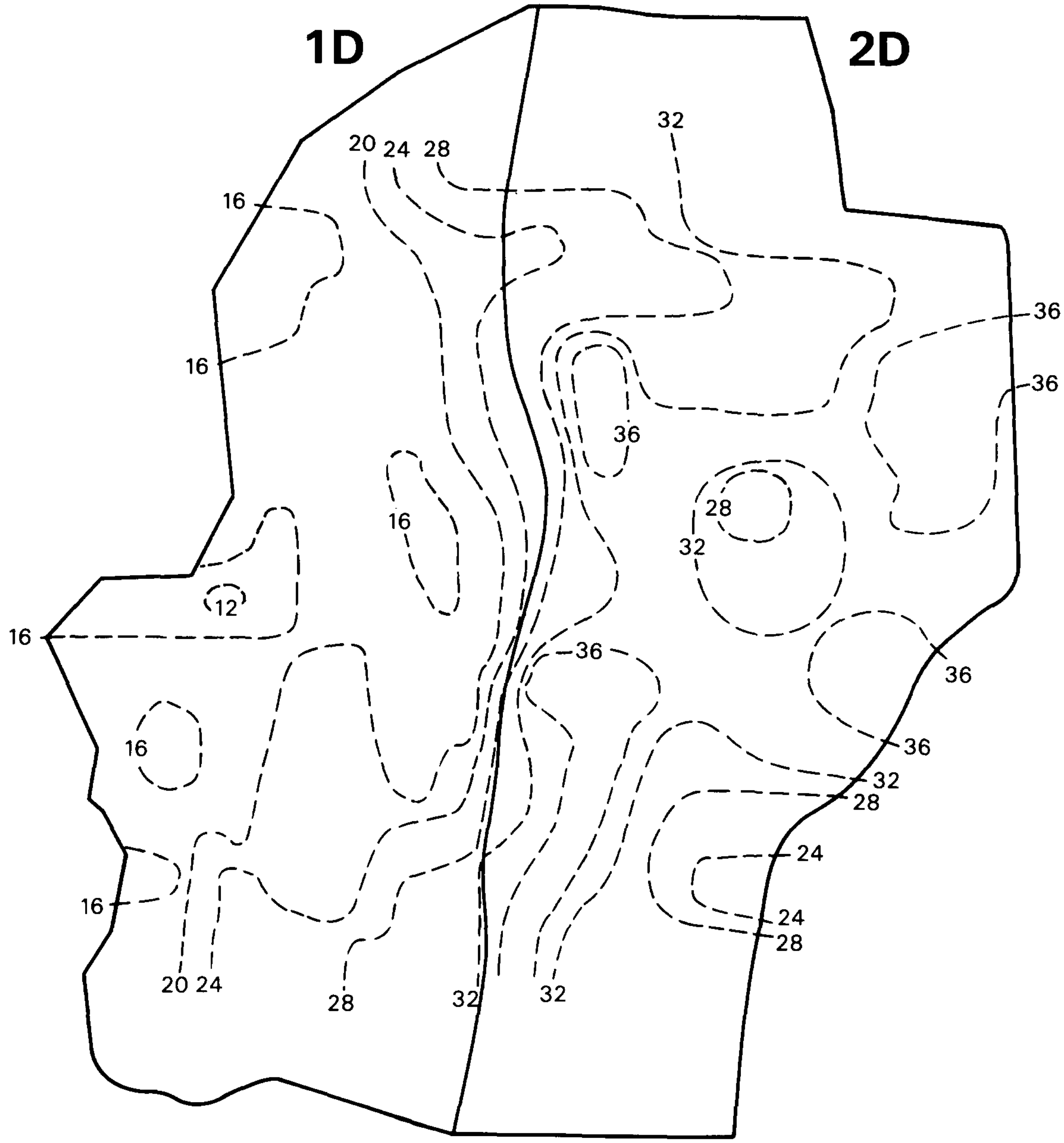


Figure 4. The soil moisture contours for the top 5-cm layer derived from the radiometric measurements on 4 June 1987.

boundary. This is because the burnt watershed 1D loses soil moisture more rapidly than the unburnt watershed 2D through direct evaporation from the soil and the higher transpiration losses from the more rapidly growing grass in 1D. In some regions of 1D watershed soil moisture decreases from 40% or more on 28 May to 12–16% on 4 June, while in the 2D watershed the soil moisture only decreased from over 40% to 24–28% during the same period. Presumably the two soils are approximately the same and, indeed, Soil Conservation Service (SCS) mapping, texture, and organic matter analyses of

Table 2.

Field	*Slope*	*exp*$(-h-2g)$	$h+2g$	W_{veg}	$2g$	h
Bare	0.0094					
1D	.0073	0.78	0.24	0.6	0.14	0.1
2D	.0051	0.54	0.61	1.2	0.28	0.33

soil samples from these two watersheds indicate little or no difference. Thus it appears that the biggest factor in the difference is the effect of the dead vegetation slowing the direct evaporation from the soil surface. This is also reflected in the higher (by 1 or 2°C) IR temperatures for 2D.

While much of the variation across both watersheds can be attributed to topographic effects, i.e., the uplands and slopes drying out more rapidly, a comparison with a satellite image obtained from the SPOT satellite indicates that the drier locations generally correspond to bright spots on the image. These bright spots are areas of thin soils with some exposed rock. The spatial distribution of soil moisture also may represent the hydrologic redistribution of soil moisture that occurs in natural basins. The PBMR-produced soil moisture maps appear to be in enough detail to identify and delineate wet areas that produce base flow by soil drainage. More research needs to be done to see if these types of maps can identify hydrologically active areas.

Finally, two small regions in 2D watershed show a persistent trend during the drying-down. The region with 40% contour in the middle of the watershed in Fig. 3 can be identified with the 28% contour at about the same location in Fig. 4. The region northwest of that location remains wet, in both figures, compared to the surrounding areas. This implies the consistency in the whole series of radiometric measurements.

CONCLUSION

A series of L-band radiometric measurements were made over two small watersheds in Konza Prairie, Kansas following a heavy rainfall. These two watersheds had undergone different surface treatments and showed a marked difference in the loss rate of surface soil moisture during the dry-down period. The two-dimensional soil moisture maps derived from the radiometric measurements clearly displayed spatial variability of this dry-down trend in the watersheds. This soil moisture mapping with a multiple-beam microwave radiometer may be potentially valuable in watershed hydrology for the identification of runoff producing areas and groundwater recharge zones.

From these results it is clear that vegetation can have a very significant effect on the retrieved soil moisture values and that the magnitude of the effect is generally proportional to the biomass of the overlying vegetation (Schmugge et al., 1986). For green vegetation it may be possible to estimate its biomass from visible and near infrared observations. However, we know of no remote sensing approach for determining the presence of a thatch layer as in these unburned watersheds. Fortunately their occurrence is relatively rare.

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